16O Coulomb dissociation

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Chapter 5

Conclusion and outlook

5.1 Discussion

The measurement of the angular distribution of $^{16}O^{*}$ was undertaken to determine the reduced transition probability for excited states in ^{16}O on basis of comparison to ECIS calculations. The free parameter is the deformation length as described in section 2.2.3. This method assumes that the usual assumption of the deformed-potential model, i.e. the equality of the deformation lengths of the potentials, is accepted.

It is of high importance for the astrophysical aim of a Coulomb-dissociation experiment to prove that what is measured is fully understood, i.e. correctly described by the model calculations. Only this can allow to disentangle the Coulomb and nuclear contributions. This is why the verification of the method with a measurement for well-known states is important. For these cases, the deformation parameters are known from the resonance strengths and allow to check the procedures and methods of measurement.

In order to obtain a comparison between experimental data and calculations, the experimental efficiencies and acceptances need to be determined. The only practical way is by means of Monte-Carlo simulations. The main inputs are the cross section and the angular correlations of the fragments, described in section 2.2.3. The trajectories of the scattered $^{16}O^{*}$ and of the fragments are sampled according to the DWBA and coupled-channel calculations. These are used to determine whether they match the angular and momentum acceptances of the BBS. Next, the horizontal position and the angles of each fragment in the focal plane are calculated with the first-order transfer parameters of the spectrometer (see eq. 3.3). The element $(\phi|\delta\phi)$ is empirically estimated from the data, while the other transfer-matrix elements are given in tables 3.1 and 3.2. It is then verified if neither of the fragments hits the blocker or arrives outside the sensitive area of the CSC's or of the scintillators. Each fragment must end up in a different scintillator set. Finally, cuts are applied as described in fig. 3.2 and in section 4.2. The specific efficiency of the setup is then given by the ratio of the number of the accepted events to that of the input events. The specificity requires that the efficiency needs to be determined for each resonance independently.

The ECIS calculations sampled with the specific efficiency of the setup described in the previous section are plotted for both 2^+ resonances in fig. 5.1, to allow comparison with the data. To elucidate the role of the nuclear and Coulomb processes and their interference, calculations for either contribution were made. Neither of the processes separately would describe the data. The interference is essential for the description. The combined results appear to describe the data satisfactorily.

The calculations using the folded-potential model as described in section 2.2.3 were also sampled with the setup efficiency. The result is plotted in fig. 5.2 in comparison with the data. The model shows a yield more than 50% below the experimental value.

The angular distribution of $^{16}O^*$ is quite well reproduced by the phenomenological deformed-potential model for most of the data points. Especially the destructive interference pattern seems to be well described. Moreover, the integrated cross section over the measured region is shown to be very well measured. For the state at 11.52 MeV, the minimum χ^2 was found for a deformation length only about 5% lower than that calculated from the literature data ([Ajz86]), as explained in section 2.2.3. Such a measurement would lead to only a 10% error in the reduced transition probability and thus in the cross section. This is actually comparable to the systematic error in the normalisation of the data, which was estimated earlier to be 7%. This supports strongly that the DWBA calculations describe relatively well the excitation process including both Coulomb and nuclear interactions and their interferences. Therefore, this implies that the method can be used to measure the deformation parameters via a fit. The discussion point is the nuclear com-

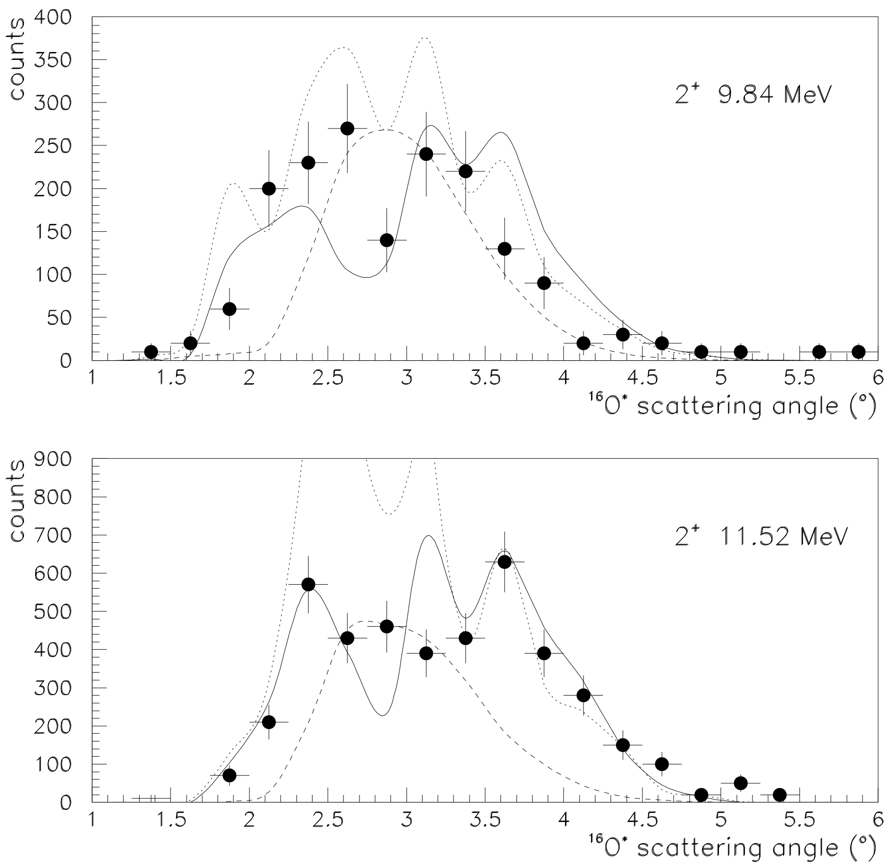

Figure 5.1: *Differential cross section of $^{16}O^{*}$ for both states. The black dots are data from the final experiment, the lines are the ECIS calculations described in section 2.2.3 (fig. 2.8), sampled with a transfer matrix estimated from a Monte-Carlo simulation. The dotted line is a pure nuclear calculation, the dashed line is pure Coulomb, and the solid line includes both interfering interactions. The destructive interference near 3° is clearly identifiable in both cases.*

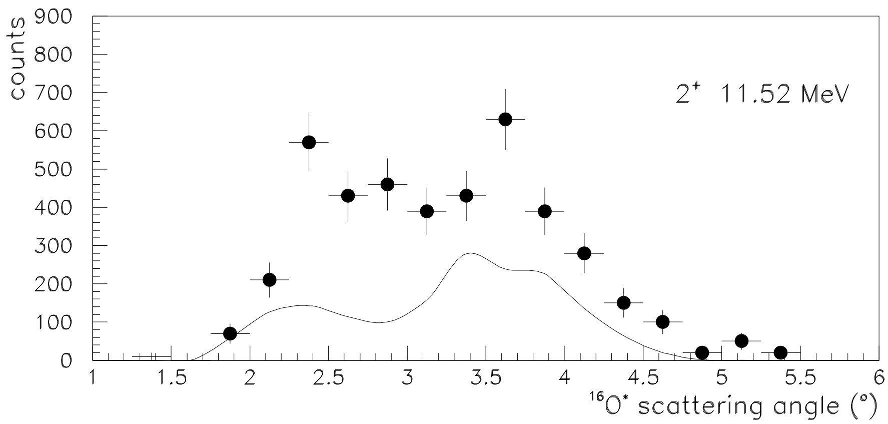

Figure 5.2: *Angular distributions of $^{16}O^{*}$ for the 2^{+} state at 11.52 MeV. The black points are data from the final experiment, the lines are the folded-model calculations, sampled with the setup transfer matrix estimated from a Monte-Carlo simulation. This model shows a large discrepancy with the data.*

ponent amplitude that shows a large cross-section discrepancy between the deformed-potential and the folding-potential models. The data imply that the phenomenological deformed-potential model as implemented in ECIS is more accurate in our case than the folding-potential model. In the future, this issue should be resolved by an independent test of the models on the 2_1^+ state in ^{16}O, under the same experimental conditions as for the unbound 2_2^+ and 2_3^+ states. This should be done by the measurement of the differential cross section of the inelastically-scattered ^{16}O nuclei excited to the 2_1^+ bound state at 6.92 MeV.

The simulations also provide predictions for the angular correlations of the fragments in the ^{16}O* centre of mass. The results are plotted separately for both states in figs. 5.3 and 5.4. The figures show that the angular correlations as a function of the polar angle are globally well reproduced if not very accurately for the points at 55° and 65° in both cases. Both angular correlations as a function of the azimuthal angle display the typical quadrupole distribution pattern. The state at 11.52 MeV is nearly perfectly reproduced. The state at 9.84 MeV shows a yield twice too strong for three points around 180°, while it is relatively good at other angles. The fact that this state has a complex excitation process might be the reason why this is not reproduced by the calculations. There is no model that predicts a strong coupling between continuum and other excited states [Har02]. Thus, the low-energy continuum of ^{16}O is excited directly from the ground state, and this should not be an issue for future experiments aiming to measure at excitations energies of relevance for stellar burning.

The current procedure assumes that the strength of the E1 excitation is low enough, which is obviously the case for 2^+ states. For a continuum measurement, the Coulomb excitation process and the fact that ^{16}O, ^{12}C and α are self-conjugate nuclei favour the quadrupole contribution. Nevertheless, the dipole part is present and must be measured and extracted. This can be done by a measurement of the fragment angular correlation. We showed that we could indeed measure this correlation for a 2^+ state. In principle, the E1–E2 interference pattern should also be measurable in the continuum, and thus permit a separation of both contributions. A better test could be done by measuring the two-dimensional correlation of the fragments instead of its projections on the θ_{cm} and ϕ_{cm} axes, but this requires high statistics.

5.2 Concluding remarks

For more than 25 years, physicists have been trying to improve the knowledge of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate at stellar energies. Imaginative efforts have been developed in various directions, but despite progress, the current situation remains unsatisfactory, leaving an important parameter largely undetermined in stellar evolution models. The direct-capture methods are technically limited and the progress that can be expected with these in the near future will probably not solve the problem in a clear-cut way.

Indirect methods seem now to be the best approach for the very low cross-section measurements of reactions, that are common in astrophysics. The Coulomb-dissociation method is arguably one of the best ways to measure the E2 component of the carbon-helium cross section at

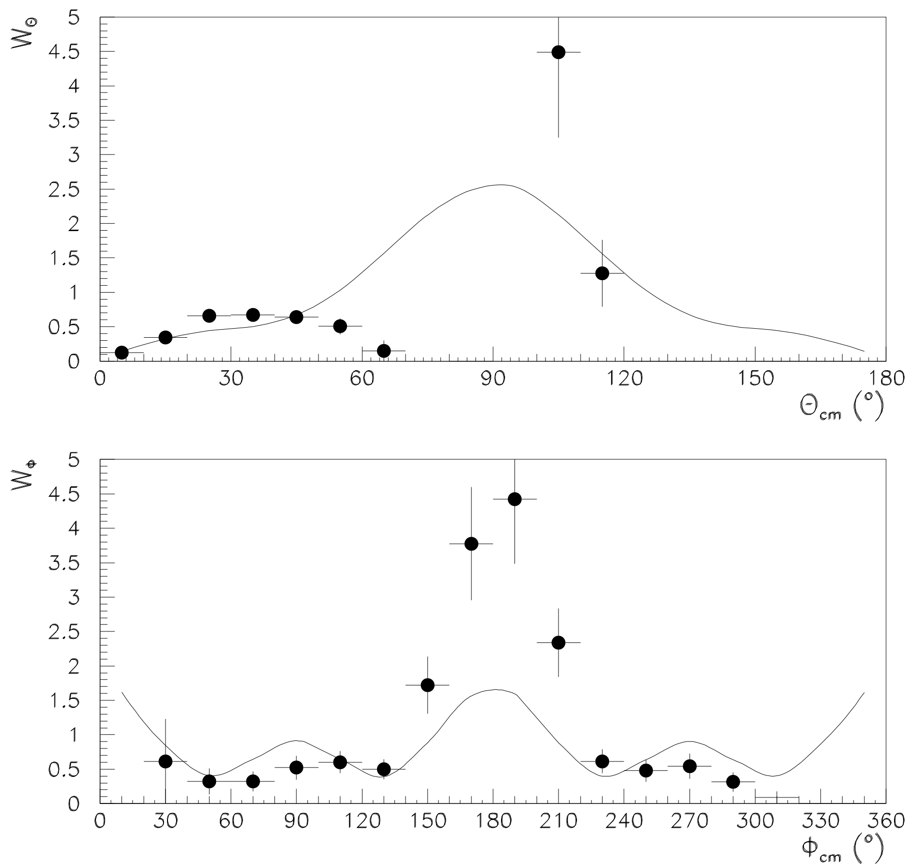

Figure 5.3: *Fragment angular correlations for the 9.84-MeV resonance. The choice of the carbon data shown is arbitrary.*

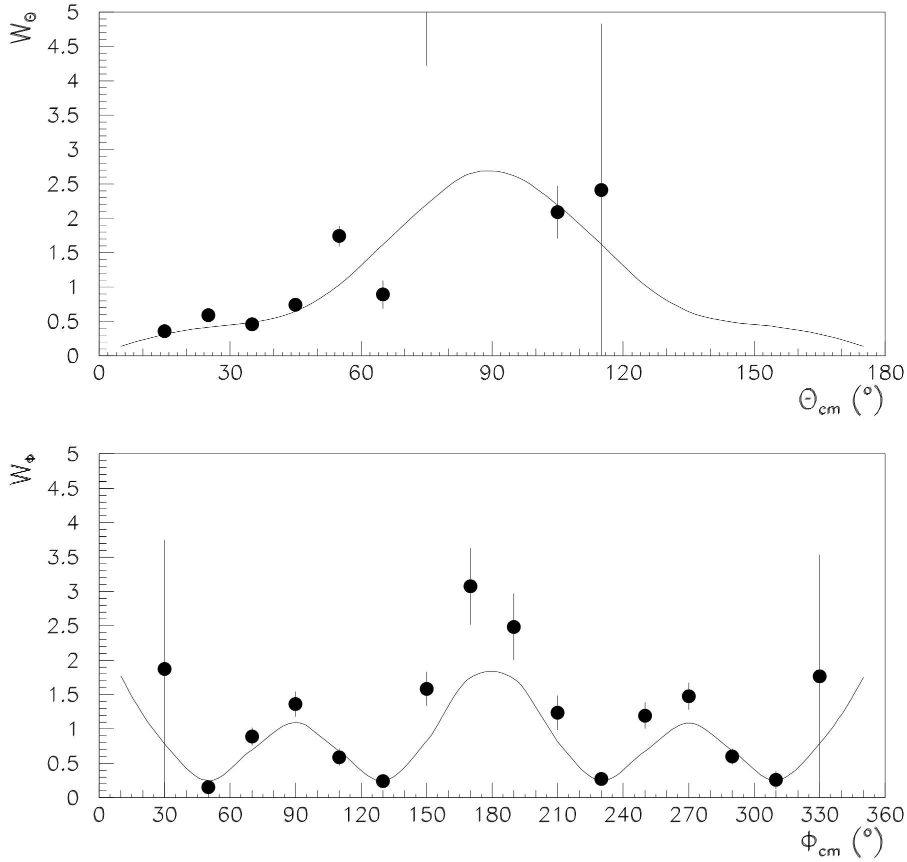

Figure 5.4: *Same as fig. 5.3 but for the 11.52-MeV resonance. In the top figure, the data point at 75°* has a value 14.3 ± 10.1.

low energies. In this way it is comparable in importance to the β-delayed α decay of ^{16}N for the E1 contribution.

Critical remarks have been made regarding the difficulties of the indirect methods [Fra98], experimental as well as theoretical. We hope this work has answered at least some of them. We especially demonstrated that technical difficulties, even as large as in the present case, can be handled and allow to produce satisfying results. Furthermore, a clear verification of this method is imperative. This work shows that it is possible to test the Coulomb-dissociation method with the measurement of resonant states. This and previous works by Tatischeff and Kiener [Tat95, Tat96] may prove that one can indeed extract the various contributions involved in this reaction and hence to use this method to estimate the capture cross section.

It is highly encouraging that in spite of the difficulties we had to face, we could produce precise energy and angular measurements with an accuracy of the order of the systematic error. We show that even in difficult circumstances, the angular distribution of ^{16}O* in the laboratory can be measured and the deformation parameter can be estimated with a good accuracy by a fit with the ECIS code. Therefore, the reduced transition probability and eventually the photonuclear cross section can be determined. Also essential is that the fragment angular correlations can be accurately measured and should allow to separate the various multipole contributions at lower energies.

It is now likely that the Coulomb-dissociation method developed by Baur et al. is in a good shape, and that it can be applied to such a difficult reaction as ^{12}C$(\alpha,\gamma)^{16}$O. Actually, the crucial points have always been the verification of the method and the importance of nuclear effects compared to Coulomb excitation. It is well-known that DWBA and coupled-channel calculations, where both nuclear and Coulomb interactions are properly included, are well suited to reproduce with precision observables like cross sections and angular distributions (see for example [Har76]). In this work, we have shown that this can also simulate correctly the fragment angular correlations.

The ultimate test of the method applied to ^{12}C$(\alpha,\gamma)^{16}$O is the comparison of the Coulomb-dissociation measurements in the continuum with the direct-capture measurements already published. The extraction of the Coulomb amplitude and the separation of E1 and E2 contributions should allow this comparison. A good correlation between the capture rate at high energy and those determined via the Coulomb-dissociation method should definitely remove any left ambiguity.

5.3 Summary

The goal of this work was to test the validity of the Coulomb-dissociation method applied to ^{16}O breakup with the study of known 2^+ states in ^{16}O. This experiment requires a large-acceptance setup in order to detect in coincidence the α and ^{12}C fragments from the breakup and to be able reconstruct their angular correlations in the centre of mass of the breakup. In this purpose the large-acceptance Big-Bite Spectrometer (BBS) at KVI was equipped with light-ion detectors that consist of position-sensitive Cathode-Strip Chambers (CSC) and two sets of scintillators. This setup allowed us to determine the particles of interest and to measure the energies and trajectories of the fragments in the BBS focal plane. A Monte-Carlo simulation was necessary to build the transfer matrices of the setup in order to reconstruct the energies and angular correlations of the fragments, as well as the ^{16}O* angular distribution. We showed that these observables are possible to measure and are well reproduced by DWBA calculations. Therefore, a further experiment could be carried out in order to measure the cross section at astrophysical energies.

5.4 Outlook

Eventually, a future experiment performed under better conditions should provide an accurate measurement of the scattering angle and of the correlations of the fragments at low energies. This will allow to estimate the astrophysical S factor for the E2 contribution with a relatively high precision.

In ideal circumstances, a 5 day measurement with a 20 nA beam, and all other parameters as in the final experiment described in this thesis, would produce about 500 times as many events. For instance, the excitation cross section in the continuum between +1.35 and +1.45 MeV above the threshold is estimated to be approximately $1/1000^{\text{th}}$ of that of the resonance at +2.68 MeV (9.84 MeV) [Tat96]. Moreover, a Monte-Carlo simulation shows an efficiency of the setup at this lower energy twice higher than for the resonance. Thus, eventually, the number of events at this energy is of the same order of magnitude as observed for this resonance. Comparing to the data of previous works (see fig. 1.5) one can roughly expect 25 times more counts at this energy than any former experiment.

Our results show that another experiment is worthwhile. The Big-Bite Spectrometer has been shown to be well suited for this type of measurement, as a large-acceptance setup is necessary to reconstruct the correlation of the fragments. However, it should be possible to concentrate on the ϕ_{cm} correlation, which is the most sensitive to the multipolarity of the excitation process. This can be achieved by using the spectrometer in mode A, which has a larger opening angle (13 msr). This mode has a smaller momentum bite, which will cause an efficiency loss for high relative-energy events. The resonances have anyway a high cross section.

The measurement should be carried out in the region where the Coulomb and nuclear contributions are interfering. A measurement at smaller and larger angles, where the nuclear contribution is dominant, would also be of interest to test the validity of the DWBA approach, and of the optical potential and deformation parameters. Since the nuclear interaction is supposed to be known poorly, a correct interpretation of the observable nuclear effect by ECIS would be a strong argument in favour of the DWBA calculation. As mentioned in section 5.1, the ECIS calculations for the 2^+ differential cross section, including the nuclear and Coulomb interfering components, should be checked independently with the measurement of inelastically-scattered $^{16}O^*$ nuclei excited to the 2_1^+ bound state at 6.92 MeV.

It was shown that shifting the 'bow-tie' knot to the high-momentum side of the focal plane gives good results (see section 3.1). It would be highly advantageous to set the BBS such that the focal plane be situated before the position-sensitive detectors, exactly at the position of the blocker. This would greatly minimise the count rate and the random coincidences due to the elastically-scattered particles. Moreover, it would allow a relatively narrow blocker, and thus a measurement of very low relative-energy events.

It is clear that measurements of the continuum cross section at low energies can be carried out only if the detection setup is optimal. It was shown in section 3.2.2 that with the ideal BBS resolution, one could safely measure the continuum cross section down to 1 MeV with less than 10% systematic uncertainty. Since this uncertainty is understood and results from an overestimation due to the exponential part of the cross section, an algorithm should be built in order to deconvolute it. The deconvolution requires a precise knowledge of the resolution dependence on relative energy. The resolution at low energies can be determined with the 2^- states that decay to 930 keV and 1.37 MeV relative energy.

The next decisive experiment should measure the continuum cross section and separate the E1 and E2 components as described in this thesis. A comparison with the direct-measurement data that exist at this energy would be an ultimate verification of the Coulomb-dissociation method. The measurement at very low energy, below 1 MeV where almost no data exist would be accepted with more confidence. If the E1 component is sufficiently strong at low energy, it would be interesting to verify the matching with the ^{16}N decay data.

Such an experiment has to be carried out at nearly ideal conditions. The horizontal and vertical resolutions of the position measurement in the focal-plane detectors is the crucial point. The BBS is now equipped with the EuroSuperNova (ESN) detector system [Han01]. This detector has been designed for protons and α particles. Nonetheless, we already showed during a test run that the two Vertical Drift Chambers (VDC), which are the first components of ESN, are able to measure accurately the position of ^{12}C ions in the focal plane. The achieved angular resolution was 2.7 mrad for θ_T and 7.8 mrad for ϕ_T. These values are highly encouraging and a new experiment is considered [Wor01] with these detectors and the BBS at KVI.